LBNL-58446

LPM Interference and Cherenkov-like Gluon Bremsstrahlung in Dense Matter

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(February 9, 2008)

Gluon bremsstrahlung induced by multiple parton scattering in a finite dense medium has a unique angular distribution with respect to the initial parton direction. A dead-cone structure with an opening angle $\theta_0^2 \approx 2(1-z)/(zLE)$ for gluons with fractional energy z arises from the Landau-Pomeranchuck-Migdal (LPM) interference. In a medium where the gluon's dielectric constant is $\epsilon > 1$, the LPM interference pattern is shown to become Cherenkov-like with an increased opening angle determined by the dielectric constant $\cos^2\theta_c = z + (1-z)/\epsilon$. For a large dielectric constant $\epsilon \gg 1 + 2/z^2LE$, the corresponding total radiative parton energy loss is about twice that from normal gluon bremsstrahlung. Implications of this Cherenkov-like gluon bremsstrahlung to the jet correlation pattern in high-energy heavy-ion collisions is discussed.
PACS numbers: 12.38.Mh, 24.85.+p; 13.60.-r, 25.75.-q

I. INTRODUCTION

The two most striking experimental observations in central $Au + Au$ collisions at the Relativistic Heavy-ion Collider (RHIC) are the large collective flow [1] and strong jet quenching [2,3] that are believed to be the experimental evidence [4,5] for the formation of strongly interacting quark-gluon plasma (sQGP). The observed strong collective flow is measured by the azimuthal anisotropy v_2 which results from the initial energy density or pressure and geometric ellipticity of the dense matter [6]. The measured v_2 was found to reach the hydrodynamic limit of a perfect fluid with extremely small viscosity [7,8]. Jet quenching or the suppression of high p_T hadron spectra, on another hand, is caused by parton energy loss [9] as the energetic parton jet propagates through the dense medium. Phenomenological analyses of the jet quenching pattern based on parton energy loss reveal an initial parton density that is about 30-40 times higher than in a cold nuclear matter [10–12]. Such a density is also consistent with the hydrodynamical analysis of the observed collective flow [8].

In an effort to recover the energy lost by the leading hadrons, one finds indeed an enhancement of soft hadrons along the direction of the initial parton jets [13,14] as determined by the opposite direction of the triggered high p_T hadron. These soft hadrons, however, have a much broadened angular distribution which peaks at a finite angle away from the initial jet direction. This is quite different from the distribution in pp collisions which peaks along the direction of the initial jet. Such a phenomenon has been attributed to Mark cone or conical flow [15–17] caused by the propagation of a supersonic jet through the dense medium. The same angular pattern could also be a result of Cherenkov gluon radiation [18,19]. However, as pointed out in Ref. [20] and will be discussed later in this paper, the total energy loss caused by Cherenkov gluon radiation is very small as compared to radiative energy loss induced by multiple parton scattering [21–26]. Therefore, it cannot be the dominant cause of the observed jet quenching and the induced soft hadron production.

This paper will discuss the angular distribution of gluon bremsstrahlung induced by multiple scattering of a fast parton in a medium that has a gluonic dielectric constant $\epsilon > 1$ and the consequences on the total radiative energy loss. We start with an analysis of the bremsstrahlung of light-like gluons induced by multiple scattering that has a unique angular distribution determined by the gluon formation time relative to the medium size due to the Landau-Pomeranchuck-Migdal (LPM) interference. The results are then extended to the case when gluons acquire a space-like dispersion relation in the medium due to a large dielectric constant $\epsilon > 1$. The angular distribution of the space-like gluon bremsstrahlung will then be shown to peak at an angle solely determined by the gluon dielectric constant ϵ in the medium. Such a Cherenkov-like pattern is shown to be the result of the LPM interference in induced bremsstrahlung of gluons with a large dielectric constant or index of refraction $n = \sqrt{\epsilon}$. Other features of the Cherenkov-like gluon bremsstrahlung and consequences on the soft particle distribution induced by jet quenching in high-energy heavy-ion collisions will also be discussed.

II. LPM INTERFERENCE AND THE DEAD-CONE

Gluon bremsstrahlung induced by multiple scattering of a fast parton in a dense medium has been shown to possess many interesting features [21–26] due to the LPM interference in QCD. One of the unique features is the quadratic length (L) dependence of the parton radiative energy loss in a finite and static medium. This is a consequence of the LPM interference and the unique feature of

gluon radiation in QCD. The most important contributing factor is the interaction of the gluonic cloud surrounding the propagating parton with the medium and the resulting gluon bremsstrahlung. Such non-Abelian LPM interference should also be manifested in the underlying final gluon spectra.

In the framework of twist expansion, the gluon spectra induced by double scattering of a fast quark with energy E in a static dense medium has been obtained in Ref. [26] as,

$$\frac{dN_g}{dzd\ell_T^2} = P(z)\alpha_s^2 \widetilde{C} m_N L \frac{1}{\ell_T^4}\left[1 - e^{-(L/\tau_f)^2}\right], \qquad (1)$$

where z and ℓ_T is the gluon's fractional energy and transverse momentum, respectively. $P(z) = [1 + (1-z)^2]/z$ is the quark-gluon splitting function and $\tau_f = 2z(1-z)E/\ell_T^2$ is defined as the gluon's formation time. The above result is obtained for a quark propagating through a cold nucleus with a Gaussian density distribution $\rho(r) \sim \exp(-r^2/2L^2)$. The parameter $\widetilde{C} m_N$ represents the gluon correlation strength and m_N is the nucleon mass introduced only for the convenience of normalization. In a hot QCD medium, $\alpha_s \widetilde{C} m_N \sim \mu^2 \sigma_g \rho_0$ [10] with μ the Debye screening mass, σ_g the parton-gluon cross section and ρ_0 the average gluon density. Here, one has used the relation $\alpha_s x G(x) \sim \mu^2 \sigma_g$ as the gluon density probed by the propagating parton in the medium.

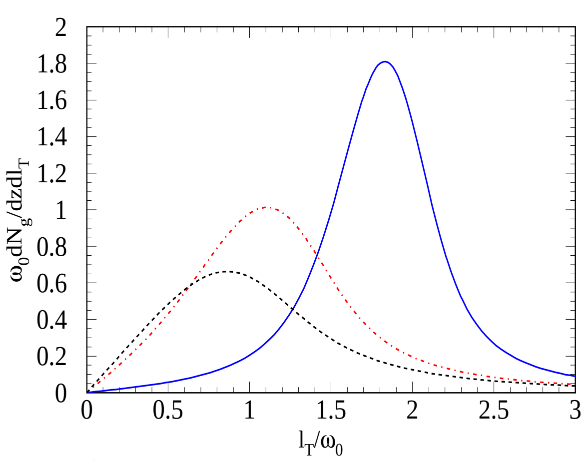

FIG. 1. Angular distribution of gluon bremsstrahlung induced by multiple parton scattering: $\omega_0 dN_g/dzd\ell_T$ versus ℓ_T/ω_0, where $\omega_0 \equiv \sqrt{2Ez(1-z)/L}$. Gluon spectra is scaled by $P(z)\widetilde{C}\alpha_s^2 L m_N/\omega_0^2$ and the gluon's fractional momentum is set $z = 0.2$. The dashed line is for ordinary gluon bremsstrahlung with LPM interference as given by Eq. (1). The solid and dot-dashed lines are the distribution in Eq. (4) for the bremsstrahlung of gluons that has a space-like dispersion relation with $-\Pi_T(\ell)/\omega_0^2 = 4$ and 1, respectively.

The above spectra is finite at $\ell_T = 0$ in contrast to the gluon bremsstrahlung in vacuum which is collinearly divergent. This is a unique feature of LPM interference in a non-Abelian theory. Because of the LPM interference, gluons with formation time $\tau_f = 2z(1-z)E/\ell_T^2$ much larger than the medium size L will have destructive interference and will be suppressed. This will lead to a depletion of gluons in the forward cone within an angle

$$\theta_0 \approx \frac{\omega_0}{zE} \equiv \sqrt{\frac{2(1-z)}{zEL}}, \qquad (2)$$

as illustrated in Fig. 1 by the dashed line. Therefore, LPM interference effectively creates a dead-cone for the gluon bremsstrahlung in the direction of the fast parton, as also pointed in Ref. [28]. The size of the dead-cone decreases both with the parton energy and medium size. The angular distribution of the bremsstrahlung gluons is peaked at θ_0 and the width of the peak is also about θ_0.

In practice, the collinear divergence in parton fragmentation will be regulated by the hadronization scale $\ell_T \sim \Lambda_{\rm QCD}$. This means any angular structure within an angle $\theta < \Lambda_{\rm QCD}/zE$ cannot be observed. This requires $zE/L > \Lambda_{\rm QCD}^2/2$ in order for the LPM interference pattern to be observed in the soft hadron spectra.

III. CHERENKOV-LIKE GLUON RADIATION

For a more complete treatment of the gluon bremsstrahlung in hot QCD medium, one should also include the effect of further interaction between the radiated gluon and the medium. At high temperature in QCD, for example, one can simply replace the gluon propagator by an effective one as one resums all hard thermal loops [27] as has been discussed in Ref. [29] in the calculation of radiative energy loss by a heavy quark. If the temperature of the QGP is just above T_c, hard thermal loop (HTL) treatment of parton interaction at finite temperature is known to fail to describe lattice QCD results [30,31]. One might expect a different dispersion relation for gluons in this region where the strong interaction between partons are non-perturbative. The empirical observation of the sQGP also indicates the non-perturbative behavior of QCD matter as created in the central $Au+Au$ collisions at RHIC. These observations have led to the suggestion that the QCD matter could become effectively composed of medium-modified (heavy) quarks and gluons and their screened Coulomb potential could lead to many shallowly bound states [32]. The strong interaction between these bound states can provide an effective mechanism for the observed small viscosity. These bound states most likely exist in the gluon sector or could be quite heavy, since abundant light quark bound states can be ruled out by the lattice study of charge and baryon number fluctuation or strangeness-baryon correlations [33]. If such gluonic or heavy bound states exist, the interaction between gluon and these bound states could lead to a space-like dispersion relation that gives rise to a gluon dielectric constant $\epsilon > 1$. A recent study within a simple model of transitional excitation of heavy particles by a light particle indeed shows a space-like dispersion relation for the light

particle in the soft region [20]. Such an effective gluonic dispersion relation was also suggested in a recent study [18] of Mach-cone-like density excitation by a space-like longitudinal plasmon mode (or Cherenkov radiation).

For the purpose of studying the pattern of Cherenkov-like gluon radiation induced by multiple scattering in this paper, let us simply assume an effective space-like dispersion relation for gluons. Therefore, the gluon propagator will have a general form

$$D^{\mu\nu}(\ell) = -\frac{\mathcal{P}_T^{\mu\nu}}{\ell^2 - \Pi_T + i\epsilon} - \frac{\mathcal{P}_L^{\mu\nu}}{\ell^2 - \Pi_L + i\epsilon}, \tag{3}$$

where $\mathcal{P}_T^{\mu\nu}$ and $\mathcal{P}_L^{\mu\nu}$ are the transverse and longitudinal projector, respectively. As an illustration of the consequences of the space-like gluon dispersion relation in this paper, we focus only on the transverse part in the calculation of induced gluon bremsstrahlung. We will also use the corresponding spectral function for the final gluons. We assume $\mathrm{Re}\Pi_T(\ell) < 0$ in the dispersion relation $\ell^2 - \Pi_T(\ell) = 0$ and that the imaginary part $\mathrm{Im}\Pi_T(\ell) \ll 2[\vec{\ell}^2 + \mathrm{Re}\Pi_T(\ell)]$ [20] in the regime of our interest so that these soft gluons are not damped during the propagation through the medium. With these simplifications, the calculation of induced gluon bremsstrahlung via multiple scattering is very similar to the normal case. The final gluon distribution can be obtained from Eq. (1) with the replacement $\ell_T^2 \to \ell_T^2 + (1-z)\Pi_T(\ell)$,

$$\frac{dN_g}{dz d\ell_T^2} \approx P(z)\frac{\alpha_s^2 \widetilde{C} L}{m_N}\frac{1}{[\ell_T^2 + (1-z)\Pi_T(\ell)]^2}\left[1 - e^{-(L/\widetilde{\tau}_f)^2}\right], \tag{4}$$

where $\widetilde{\tau}_f = 2Ez(1-z)/[\ell_T^2 + (1-z)\Pi_T(\ell)]$.

The above gluon spectra clearly has a very different structure for a space-like dispersion relation $\Pi_T(\ell) < 0$ from that in Eq. (1). It is peaked at $\ell_T^2 = (1-z)|\Pi_T(\ell)|$ which is independent of the medium size L, in contrast to the angular distribution of bremsstrahlung of normal light-like gluon with LPM interference. The corresponding angular distribution has also a peak structure and is strongly suppressed in the forward direction within a cone $\theta < \theta_c$ as illustrated by the solid and dot-dashed lines in Fig. 1. The width of the peak is, however, the same as the bremsstrahlung of ordinary light-like gluons with LPM interference. The shift of the peak to a larger angle depends on the value of $\Pi_T(\ell)/\omega_0^2$. For simplicity, we have set $\Pi_T(\ell)$ as independent of ℓ_T for soft gluons in Fig. 1 as an illustration. In general $|\Pi_T(\ell)|$ should depend on gluon's momentum ℓ and decreases with ℓ at large momentum. In this limit, gluons will become light-like again. With a momentum-dependent $|\Pi_T(\ell)|$, the shape and position of the peak will be slightly modified.

The above pattern of gluon bremsstrahlung is very similar to that of Cherenkov radiation. However, when cast in the form of induced radiation from multiple parton scattering, one can immediately discover a special relationship between the Cherenkov-like gluon radiation pattern and the LPM interference effect. In our case of induced gluon radiation, the Cherenkov-like bremsstrahlung is a result of complete LPM interference within the forward cone θ_c. If we express the self-energy of a space-like gluon in terms of gluon's dielectric constant $\epsilon(\ell)$,

$$\epsilon(\ell) \equiv 1 - \frac{\Pi_T(\ell)}{\ell_0^2}, \tag{5}$$

or $\epsilon(\ell) = \vec{\ell}^2/\ell_0^2$, one can find the cone-size of this Cherenkov-like gluon radiation as

$$\cos^2\theta_c = z + \frac{1-z}{\epsilon(\ell)}. \tag{6}$$

In the soft radiation limit $z \sim 0$, this corresponds exactly to the angle of classical Cherenkov radiation.

One can also compute the total quark energy loss due to the Cherenkov-like gluon radiation from Eq. (4),

$$\Delta E = E\int dz d\ell_T^2 z \frac{dN_g}{dz d\ell_T^2} \approx \Delta E_0 \times \begin{cases} 2, & \text{for}\frac{|\Pi_T|L}{2E} \gg 1 \\ \left(1 + \frac{1}{3}\frac{|\Pi_T|L}{2E}\right), & \text{for}\frac{|\Pi_T(\ell)|L}{2E} \ll 1 \end{cases} \tag{7}$$

where $\Delta E_0 \approx \widetilde{C}\alpha_s^2 m_N L^2 3\ln(E/\mu)$ is the radiative energy loss from normal gluon bremsstrahlung [10] with gluon spectra as given by Eq. (1) and μ is the averaged transverse momentum transfer for elastic parton scattering in the medium. For simplification, we assumed that $\Pi_T(\ell_0) \approx \Pi_T$ has a weak momentum dependence for soft (space-like) gluons. It is interesting to note that the total energy loss becomes twice of that from normal gluon radiation when $|\Pi_T(\ell_0)| \gg 2E/L$, which corresponds to a large gluon dielectric constant $\epsilon \gg 1 + 2/z^2EL$. In this case, the dielectric property of the medium amplifies the induced radiative energy loss.

We note, as pointed out in Ref. [20], that true Cherenkov gluon radiation without multiple parton scattering can also cause radiative energy loss. Its value, $(dE/dx)_c \sim 4\pi\alpha_s\ell_0^2/2$ is considerably smaller than the scattering-induced radiative energy loss since the typical space-like gluon energy $\ell_0 \sim T$ is rather soft, on the order of the temperature, when Cherenkov radiation is the strongest. It also has a very weak dependence on the matter density.

IV. DISCUSSIONS

We should emphasize that the gluon spectra in this paper is obtained through a simplified treatment of induced radiation of gluons with dielectric constant $\epsilon > 1$. A more complete study is needed, however, including the longitudinally polarized gluons, for more accurate calculation of the final gluon spectra. However, we expect the main

feature of our study in this paper will remain. A large gluon dielectric constant will lead to a Cherenkov-like gluon bremsstrahlung due to LPM interference. If such a medium with large gluon dielectric constant is created in high-energy heavy-ion collisions, then one should see such an angular distribution of soft hadrons in the direction of quenched jets. Such an angular distribution appears similar to that from a Mach cone caused by a supersonic jet. However, the underlying mechanisms are completely different and the distribution of produced particles is determined by different properties of the medium. The pattern of Cherenkov-like gluon bremsstrahlung is determined by the gluon dielectric constant in the medium while the cone size of the sonic shock wave is directly related to the sound velocity in the medium.

The momentum dependence of the cone size is also different between sonic shock wave and the Cherenkov-like bremsstrahlung. Since the sonic shock wave is caused by the propagation of energy at the sound velocity in the medium, the resulting Mach cone size should be independent of the final soft hadrons' momenta. On the other hand, the gluon dielectric constant has a strong dependence on the gluon momentum. In general, it decreases with the gluon momentum, so that large momentum gluons will become light-like again. Therefore, one expects to see the Cherenkov cone size become smaller and the cone will eventually disappear for high-energy gluons. This means that the angular correlation of soft hadrons will gradually become peaked in the direction of the jet when the momentum of the soft hadrons is increased. Such a difference in the momentum dependence of the angular cone size can be used to distinguish the sonic shock wave from Cherenkov-like gluon bremsstrahlung. Confirmation and measurement of such Cherenkov pattern will provide information on the fundamental and intrinsic properties of the dense medium.

As has been demonstrated, the Cherenkov-like gluon bremsstrahlung will increase the total parton energy loss by almost a factor of two if the gluon dielectric constant is really large. This will certainly affect the modification of the leading hadron spectra from fragmentation of the leading partons. One therefore has to revise the previous analyses [10–12] of the RHIC data on high-p_T hadron suppression and the extraction of the initial gluon density.

We would like to thank V. Koch for helpful discussions. This work is supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Divisions of Nuclear Physics, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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